

COST OPTIMIZATION OF STRUCTURES IN CIVIL ENGINEERING: THE MINLP



Made by: KASTAL Zahra

Supervised by: Mrs. EL MKHALET Mouna

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PRESENTATION OF THE PLAN:

I. Introduction:

- ✓ Justification for choice
- ✓ Problematic
- ✓ Solution
- ✓ What is MINLP?

II. MINLP superstructure

III. MINLP model formulation

IV. Solving the MINLP problem

V. Numerical examples:

- ✓ Cost, material and standard dimension optimization of a composite I beam floor system
- ✓ Cost, topology and standard section optimization of a single-storey industrial steel building

VI. MINLP in Morocco:

- ✓ Is it applied in Morocco?
- ✓ What are the alternatives?
- ✓ Where should it be used?

VII. Conclusion:

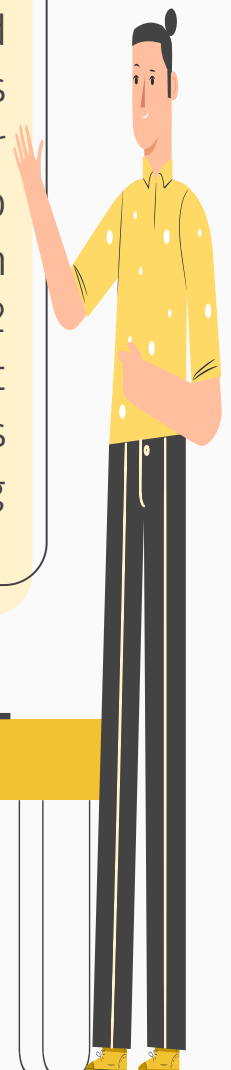
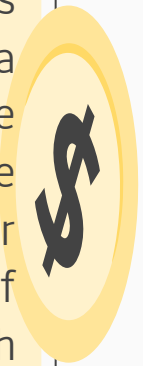
- ✓ The added value
- ✓ Expansion of the topic

VIII. References

I. INTRODUCTION



As a civil engineering student who is « building » her future and the future of a whole nation, I find it very important to be innovative and to always renew the traditional methods that are used in our domain including the calculation of structures. There was nothing wrong with this operation except for the fact that its cost CAN be lowered or « optimised » and this is where our project stands. Engineers from all around the world gathered their efforts to find an approach that is going to decrease cost and materials that interfere in construction, thus pollution and CO2 emissions. And one of the most efficient ways in cost optimization of structures is the Mixed-Integer Non-linear Programming approach, MINLP.



LET'S DIG A LITTLE DEEPER!

The MINLP handles continuous and discrete binary 0-1 variables simultaneously since they allow expressing the existence or nonexistence of structural elements inside the defined structure. Different discrete materials and standard sizes and may also be defined as discrete alternatives.

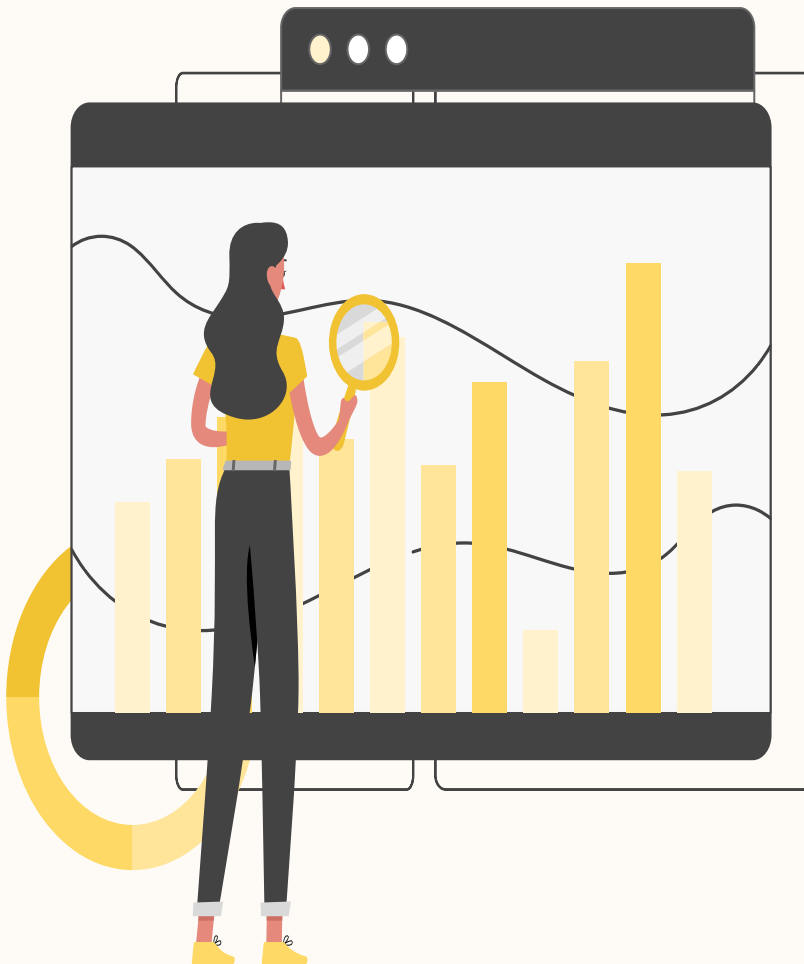
The MINLP discrete/continuous problems of structural optimization are in general difficult to be solved. The structural optimization is thus proposed to be performed through three steps:

1. Generating a mechanical superstructure of different topology, material and standard dimension alternatives,
2. Developing an MINLP model formulation
3. Finding a solution for the defined MINLP optimization problem.

This type of problems are in most cases comprehensive, non-convex and highly non-linear that's why engineers reported the experience in solving this type of problems by using the Modified Outer Approximation/Equality-Relaxation algorithm by Kravanja & Grossmann (1994).

An economic objective function of the manufacturing material and labour costs is defined for the optimization. The objective function is subjected to structural analysis and dimensioning constraints. The design constraints are defined according to Eurocodes.

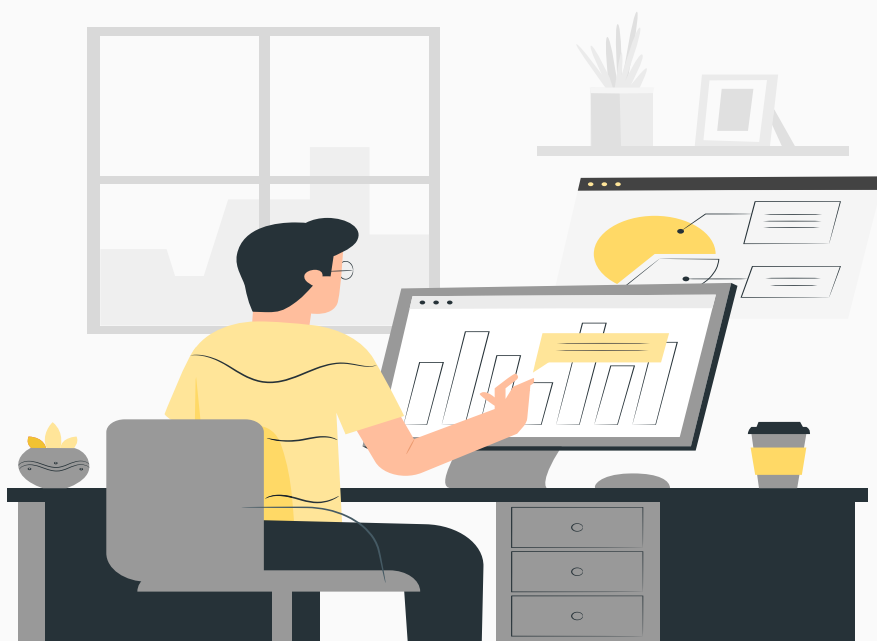
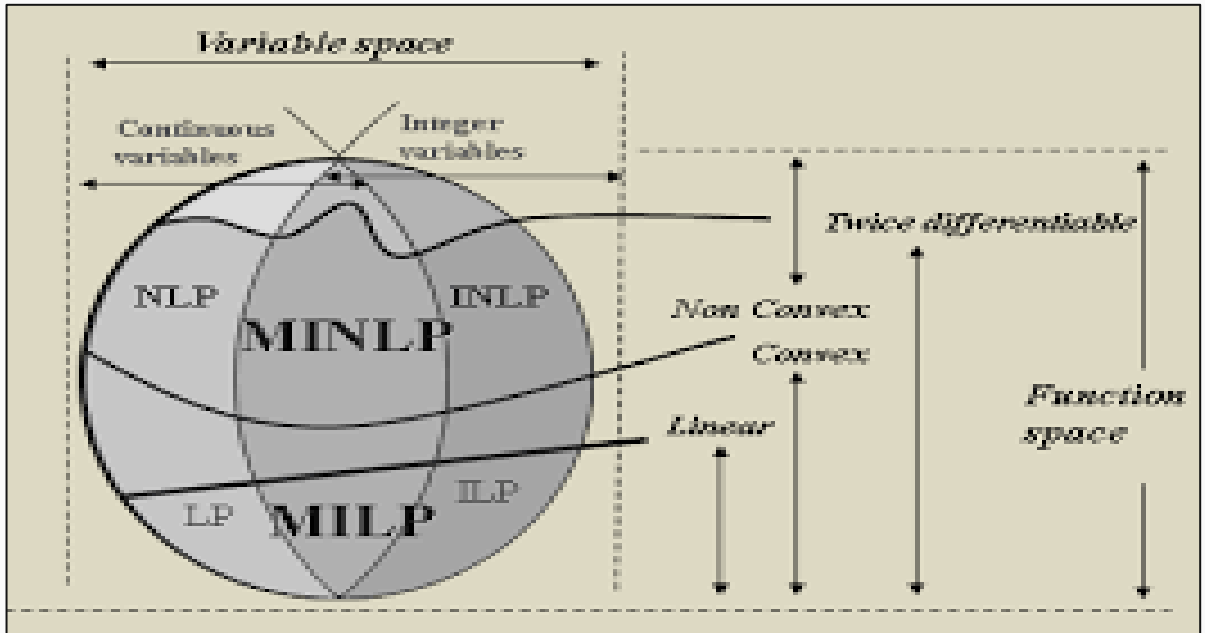
II. MINLP SUPERSTRUCTURE



WHERE TO START?

The MINLP optimization approach to structural optimization requires the generation of an MINLP mechanical superstructure composed of various topology and design alternatives that are all candidates for a feasible and optimal solution. While the topology alternatives represent different selections and interconnections of corresponding structural elements, the design alternatives include different materials and standard dimensions. The superstructure is typically described by means of unit representation: i.e. structural elements and their interconnection nodes. Each potential topology alternative is represented by a special number and a configuration of selected structural elements and their interconnections; and each structural element may in addition have different material and standard dimension alternatives. The main goal is thus to find within the given superstructure a feasible structure that is optimal with respect to manufacturing costs, topology, material and standard dimensions.

III. MINLP MODEL FORMULATION



METHODOLOGY

A general non-linear and non-convex continuous and discrete optimization problem can be formulated as an MINLP problem in the following form (see Eq. (1) to (6)):

$$\min z = c^T y + f(x) \quad (1)$$

s.t.:

$$h(x) = 0 \quad (2)$$

$$g(x) \leq 0 \quad (3)$$

$$By + Cx \leq b \quad (4)$$

$$x \in X = \{x \in \mathbb{R}^n: x^{lo} \leq x \leq x^{up}\} \quad (5)$$

$$y \in Y = \{0,1\}^m \quad (6)$$

where x is a vector of continuous variables specified in the compact set X and y is a vector of discrete, binary 0-1 variables.

Functions $f(x)$, $h(x)$ and $g(x)$ in equations (1), (2) and (3) are non-linear functions involved in the objective function z , equality and inequality constraints, respectively. All functions $f(x)$, $h(x)$ and $g(x)$ must be continuous and differentiable. Finally, $By+Cx \leq b$ represents a subset of mixed linear equality/inequality constraints.

The above general MINLP model formulation has been adapted for the optimization of structures. In the context of structural optimization, continuous variables x define structural parameters (dimensions, strains, stresses, costs, weight, etc.) and binary variables y represent the potential existence of structural elements as well as the choice of materials and standard dimensions. The economical objective function z involves fixed costs charges in the term $c^T y$ for manufacturing, while the dimension dependant costs are included in the function $f(x)$. Non-linear equality and inequality constraints $h(x)=0$, $g(x) \leq 0$ and the bounds of the continuous variables represent the rigorous system of the design, load, resistance, stress, deflection, dimensioning, etc. constraints known from structural analysis. Logical constraints that must be fulfilled for discrete decisions and structure configurations are given by $By+Cx \leq b$.

IV. SOLVING THE MINLP PROBLEM

The OuterApproximation/ Equality-Relaxation (OA/ER) algorithm by Kocis & Grossmann is selected for the optimization. The OA/ER algorithm consists of solving an alternative sequence of Non-linear Programming (NLP) optimization subproblems and Mixed-Integer Programming (MILP) master problems. The former corresponds to continuous optimization of parameters for a structure with a fixed topology (and fixed standard dimensions, discrete materials) and yields an upper bound to the objective to be minimized. The latter involves a global approximation to the superstructure of alternatives in which a new topology, standard dimensions, discrete materials are identified so that its lower bound does not exceed the current best upper bound. The search of a convex problem is terminated when the predicted lower bound exceeds the upper bound, otherwise it is terminated when the NLP solution can be improved no more. The Modified OA/ER algorithm was applied by Kravanja & Grossmann (1994). The Linked Multilevel Hierarchical Strategy (LMHS) has been developed to accelerate the convergence of the OA/ER algorithm. Using the LMHS strategy, we decompose the original integer space and original MINLP problem in a hierarchical manner into several subspaces and corresponding MINLP levels. Each time the next MINLP optimization level is performed, the current integersub space is extended by the next integer subspace and prescreened, while the discrete decisions belonging to all of the remaining subspaces are approximated by the relaxed 0-1 variables.

WHAT ARE THESE LEVELS ?

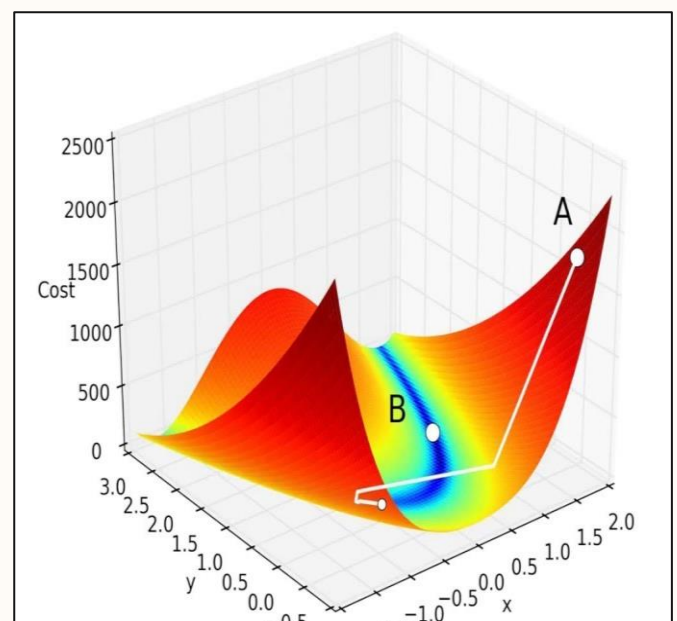
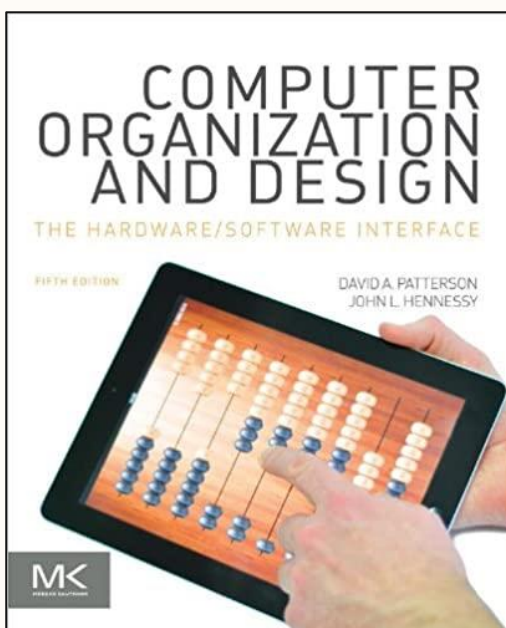
The levels are linked by accumulating outer-approximations and yield lower bounds to their next level objective functions to be minimized, which considerably improve the efficiency of the search. Decision levels are hierarchically classified into four levels:

- the level of discrete topology alternatives (the highest level),
- the level of material alternatives,
- the level of discrete standard dimension decisions (the lower level).

Higher levels give lower bounds to the original objective function to be minimized while lower levels give upper bounds. The MINLP subproblems are iterated about each level until there are no improvements in the NLP solution. Since this number of 0-1 variables is too high for a normal solution of the MINLP, we developed a prescreening procedure, which automatically reduces binary variables for standard dimension alternatives into a reasonable number.

V. NUMERICAL EXAMPLES:

The MINLP optimization approach is illustrated by two numerical examples. The optimization of the structures was carried out by a user-friendly version of the MINLP computer package MIPSYN, the successor of PROSYN (Kravanja & Grossmann) and TOP (Kravanja). GAMS/CONOPT by Drudd (1994), the Generalized Reduced-Gradient method, was used to solve NLP subproblems and GAMS/Cplex, Branch and Bound, was used to solve MILP master problems. For each type of structure, a special optimization model was developed. As an interface for mathematical modeling and data inputs/outputs GAMS (General Algebraic Modeling System), a high level language by Brooke was used.



V.I COST, MATERIAL AND STANDARD DIMENSION OPTIMIZATION OF A COMPOSITE I BEAM FLOOR SYSTEM:

The first example presents the simultaneous material and standard dimension optimization of a *23 m long composite I beam floor system*, subjected to the self-weight and to the uniformly distributed imposed load of 6.0 kN/m². The MINLP optimization model COMBOPT was developed for the optimization of composite I beams. The material and labor costs for composite beams were accounted for in the economical type of the objective function, subjected to the given design, material, stress, deflection and stability constraints, defined in accordance with Eurocodes 4. The material and labour costs for the composite beams considered are shown in Table 1. The superstructure comprised 6 different concrete strengths (C25, C30, C35, C40, C45, C50), 3 different structural steel grades (S 235, S 275, S 355), 48 various standard reinforcing steel sections as well as 9 different standard thickness of sheet-iron plates (from 8 mm to 40 mm) for webs and flanges separately. The Modified OA/ER algorithm and the LMHS MINLP strategy were applied. The optimal result of 107.11 EUR/m² was obtained in the 3rd MINLP iteration, see “Figure 1”. Beside the optimal selfmanufacturing costs, the optimal concrete strength C25/30, steel grade S 355, the reinforcement, intermediate distances between I sections, depth of the slab and optimal standard thickness of webs and flanges also were obtained.

Table 1. Material and labour costs of composite I beam floor systems.

Material costs for structural steel S 235-S 355	1.25-1.45	EUR/kg
Material costs for reinforcing steel S 400	1.45	EUR/kg
Material costs for concrete C 25/30-C 50/60	115.0-140.0	EUR/m ³
Sheet-iron cutting costs	6.5	EUR/m ¹
Welding costs	8.5	EURm ¹
Anti-corrosion resistant painting costs (R30)	24.0	EUR/m ²
Panelling costs	17.5	EUR/m ²

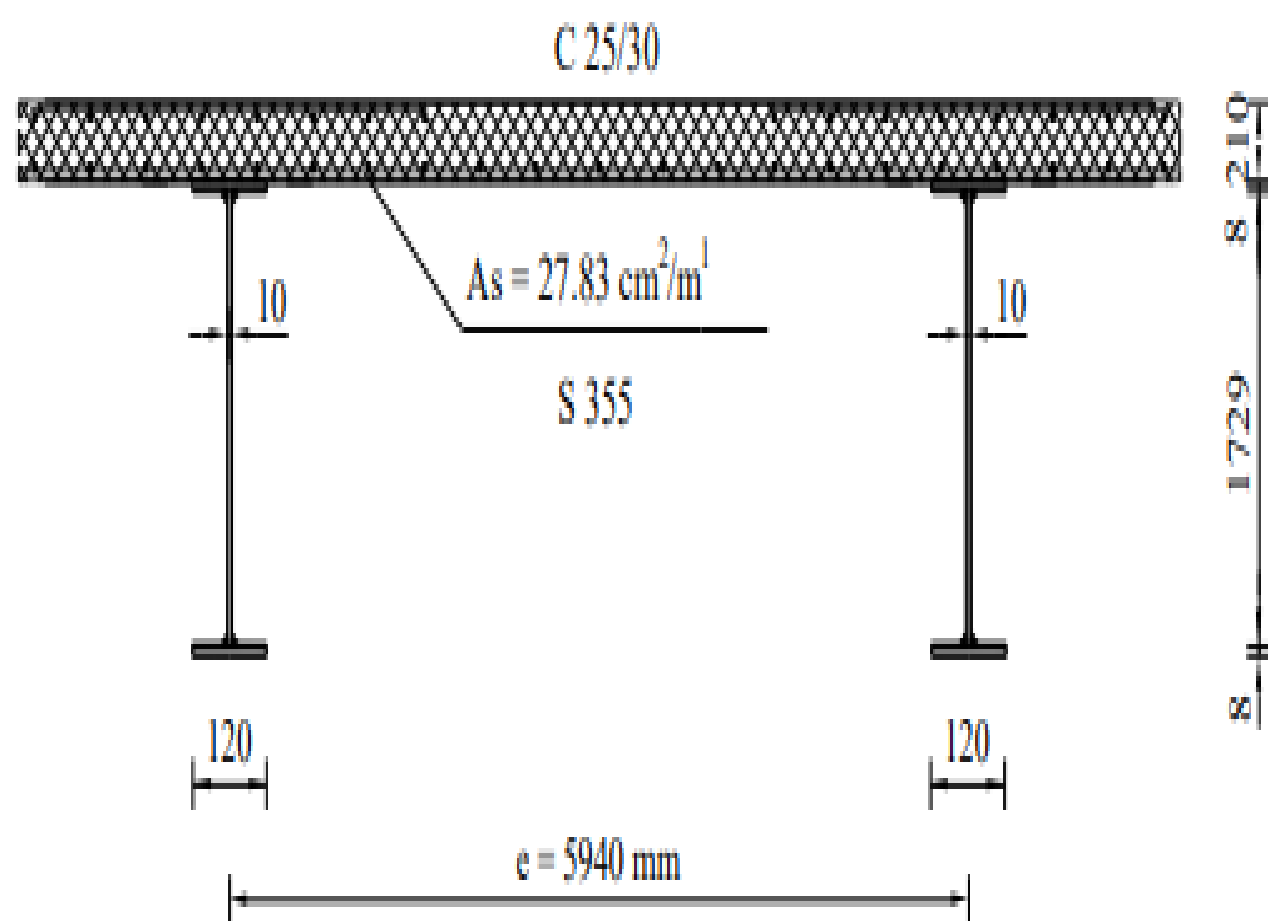


Figure 1. Optimal design of a composite I beam floor system.

V.II COST, TOPOLOGY AND STANDARD SECTION OPTIMIZATION OF A SINGLE-STOREY INDUSTRIAL STEEL BUILDING

The second example introduces the cost, topology and standard section optimization of a single-storey industrial steel building structure. The building is 26 meters wide, 70 meters long and 8.25 meters high. The structure is consisted from equal non-sway steel portal frames, which are mutually connected with purlins and rails. The structure was subjected to the selfweight and to the variable load of snow and wind. The mass of the roof was 0.20 kg/m² and of the facade cladding 0.15 kg/m². The variable imposed loads 2.0 kN/m² (snow) and 0.50 kN/m² (horizontal wind) were defined in the model input data. The task of the optimization was to find the minimal material and labor costs, the optimal topology and all standard cross-sections. The building superstructure was generated in which all possible structures were embedded by 60 portal frame alternatives, 50 purlin alternatives, 20 rail alternatives and 24 different alternatives of standard hot rolled European wide flange HEA sections (from HEA 100 to HEA 1000) for each column, beam, purlin, rail and façade column separately. The material and labour costs for the steel building considered are shown in Table 2. The MINLP optimization model HALLOPT was developed. Eurocode 3 was used for the dimensioning. *The optimal result of 435771.06 EUR was obtained in the 3th main MINLP iteration.* The optimal solution includes the obtained optimal topology of *13 portal frames, 14 purlins with the same number of secondary facade columns, and 12 rails*, see Figure 2. The main frame columns are designed from HEA 600, beams from HEA 700, purlins from HEA 160, rails from HEA 100 and the secondary facade columns from HEA 220 standard sections.

Table 2. Material and labour costs of a single-storey industrial steel building.

Material costs for structural steel S 355	1.5	EUR/kg
Anti-corrosion resistant painting costs (R30)	25.0	EUR/m ²
Erection costs per portal frame	500.0	EUR/frame
Erection costs per portal purlin	250.0	EUR/purlin
Erection costs per portal rail	250.0	EUR/rail
Erection costs per portal façade column	250.0	EUR/fc

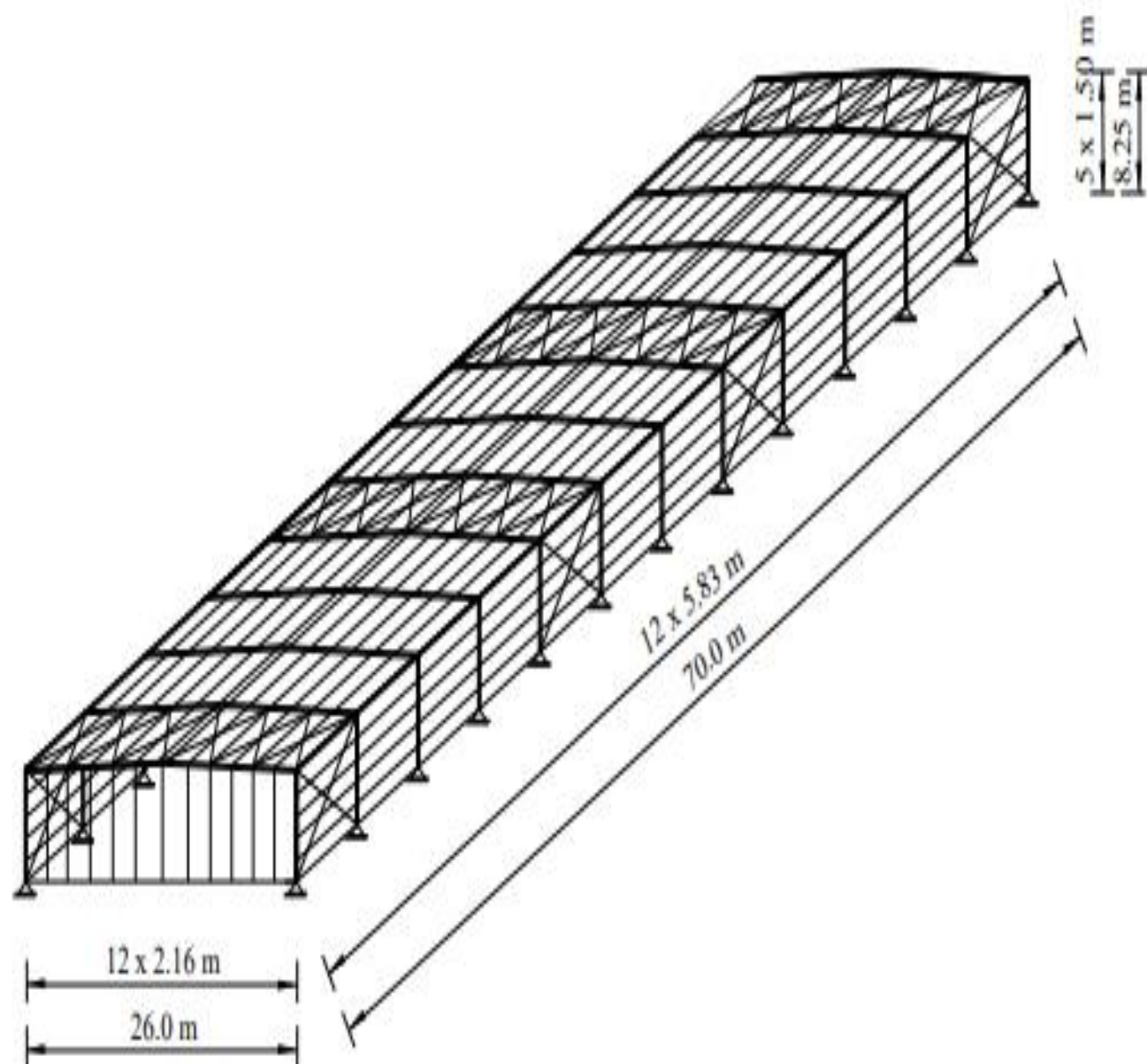
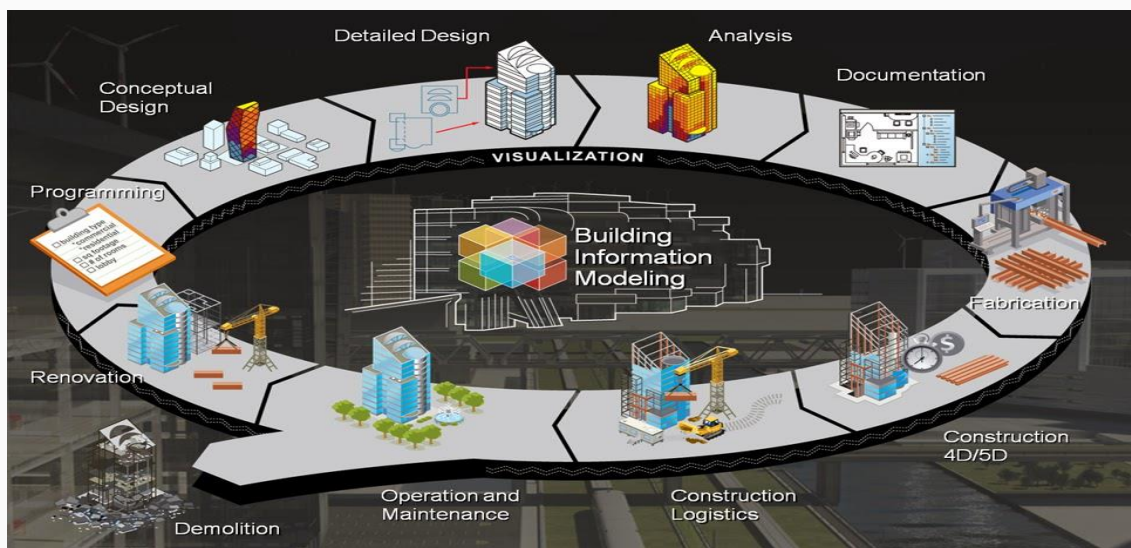


Figure 2. Optimal design of the single-storey industrial steel building.



VI. MINLP IN MOROCCO

Civil engineering in Morocco is still a little outdated. However, in the last decade, new technologies started to appear and engineers began to learn how to use softwares and invest in them such as AutoCad, Robot and BIM. Mr Mustafa FARES the CEO of LPEE (public testing and study laboratory) said: technological innovation is transforming the construction industry. BIM, "Building Information Modelin" which has been in vogue in recent years, is disrupting established processes: the intelligent 3D digital model is becoming the central element of exchanges between those working on a construction site. the role of the design office thus becomes essential from the assembly phase, called "synthesis", until the delivery of the "building avatar". Moroccan Buildings and Public Works sites are getting started slowly but surely by initiating with some major emblematic infrastructure projects. Meaning that the use of the software BIM is turning into a necessity and not just a luxury since construction costs are better controlled because they are extracted in real time. The quality of the buildings is generally improved thanks to the various analyzes and simulations carried out at an early stage of the project, before the costs of the modifications have too much repercussions.



In addition, Moroccan engineers optimize constructions' costs using ATTIQUE as well.

The ATTIQUE construction process makes it possible to optimize housing construction costs on several points. The ATTIQUE concept is based on the principle of a dry process and the industrialized GIPEN system of prefabrication of construction elements. It generates significant savings in construction.

- A quick site:

The dry process (building in wood) is much faster than the wet process (concrete requires water). GIPEN industrial solutions, based on a preliminary design in the design office and prefabrication in the workshop, integrate a maximum of components, such as insulators, facing plates, electrical ducts. As a result, they make it possible to optimize the cost, facilitate assembly on site and limit the number of workers. As the duration of the work is reduced, the financial costs of the loans are lower

- Economic gains from industrialization:

The preliminary design in the design office as well as industrialization make it possible to optimize volumes and material consumption, to make the best use of the standard dimensions of the materials and to save economies of scale.

- Absence of earthworks and foundations:

The ATTIQUE system, based on a dry wood solution, does not require earthworks or foundation repairs. The wood solution, a material 5 times lighter than concrete, can be added naturally and simply to existing structures. The use of the ATTIQUE process allows the construction of housing at 13293.94 MAD excl.VAT / m² of living space (excluding adaptations of the existing building and project management fees) The concept does not have a minimum profitability threshold, since it is based on the design and study on a case-by-case basis of a solution and an elevation proposal. All our construction systems are made to measure and are therefore adaptable to the specificities of each operation.

The two previously mentioned examples show us that in Morocco, we don't use algorithms yet. Perhaps we will see them in the future, considering the revolution of technology in the country, but so far the two methods seem to be very efficient. Let's not forget to say that the software BIM for examples must be used by the design office so that it can be obligatory on everyone and not just by one company and left as a choice .

THINGS TO KEEP IN MIND

ADDED VALUE

The MINLP is very efficient to when it comes to lowering the cost of structures in civil engineering just like the two mentioned examples have shown. It economizes costs, time and energy, and it allows the design office to have a specific idea about the project, thus avoiding construction and money related issues such as mis anticipating the needed amount of money or quantities of concrete and iron needed in the construction site. So we can see how such algorithms can make big tasks done in a shorter period of time and with less money and mistakes.

CONCLUSION

The cost optimization of structures in civil engineering is performed by the MixedInteger Non-linear Programming approach, MINLP. The Modified OA/ER algorithm and the LMHS strategy are applied. Beside the optimal structure costs, the optimal topology with the optimal number of structural elements, the optimal discrete materials and the optimal standard dimensions are obtained simultaneously. Along side with the cost optimization of structures we can figure a way to optimize water and electricity use. In other words, The thinking around optimization does not stop at the cost of construction but also extends to the costs associated with the subsequent operation of the building, and the solutions are not necessarily complex. Thus, the implementation of a dual-control flushing mechanism greatly reduces the consumption of this material. As for electricity, the architectural design must first take into account the principles of light in order to maximize the benefits of natural daylight and limit the use of artificial lighting,

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